Quarterly Progress Report 2

INVESTIGATION OF SOLID STATE TRAVELING-WAVE AMPLIFIER TECHNIQUES FOR FUTURE SATELLITE APPLICATIONS

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ABSTRACT

The objective of this program is to carry out investigations of solid-state traveling-wave amplifier techniques with emphasis on those problem areas critical to the future use of these techniques in satellite applications. Particular tasks include development of improved transducers, elimination of spurious oscillations, evaluation and selection of optimum semiconductor materials, and investigation and evaluation of properties of solid-state traveling-wave amplifier process.

The major program efforts during the period covered by this report were devoted to theoretical investigations of microwave amplifier processes and materials and to the analysis of a noise figure measuring scheme. Emphasis was placed on the development of the conditions for oscillation free amplification and low noise.

The development of thin film transducers has progressed to a very satisfactory point and effort has also been devoted to the analysis of the requirements for an rf impedance matching network to match into the amplifier's acoustic transducers. This network is designed to offer broadband rf coupling.

ACOUSTIC AMPLIFIER

I. TECHNICAL DISCUSSION

A. Introduction

1. Objective

The objective of this program is to carry out investigations of solid-state traveling-wave amplifier techniques, with emphasis on those problem areas critical to the future use of these techniques in satellite applications. Particular tasks include development of improved transducers, elimination of spurious oscillations, evaluation and selection of optimum semiconductor materials, and investigation and evaluation of properties of the solid-state traveling-wave amplifier process. An ultimate objective is a conclusive over-all evaluation of the solid-state traveling-wave amplifier as a device to perform as a conventional traveling-wave amplifier with the unique advantages of the solid state. These key potential advantages important to satellite applications include inherent simplicity, ultralight-weight, unusually small size, broad bandwidth characteristics, long life, radiation resistance, and high reliability under the arduous space environment from launch through orbit.

2. Program Plan

The objectives of this program are to be achieved by performing the following coordinated set of tasks:

TASK 1: Developing Improved Transducers

This phase involves study, fabrication and evaluation of materials and processes for improved microwave-frequency acoustic-wave transducers. Major emphasis will be placed on developing ferromagnetic and piezoelectric thin-film transducers and associated thin-film impedance matching layers. This topic will be investigated in considerable depth since the development of improved transducers is critical to subsequent phases of the investigation.

TASK 2: Eliminating Oscillations

This phase involves testing and proving the effectiveness of proposed techniques for suppressing spontaneous oscillations in the amplification process. These techniques include suppression of oscillations due to reflected waves and elimination of oscillations due to external feedback.

TASK 3: Investigating Optimum Materials

Using the improved transducers and tested techniques for eliminating oscillations of the first and second tasks, the most promising acoustic amplification materials will be evaluated. Particular emphasis will be placed on choosing the material offering the highest possible operating efficiency as a microwave amplifier.

TASK 4: Evaluating the Solid-State Amplifier

Results of the previous tasks will be combined in the design, development and fabrication of a model solid-state traveling-wave amplifier suitable for determining many of the performance characteristics of the amplification technique. This investigation will provide initial data on size, weight, gain, efficiency, bandwidth, frequency range, noise performance, life and reliability.

3. Progress Summary

The major program efforts during the period covered by this report were devoted to theoretical investigations of microwave amplifier processes and the most applicable materials according to their various electrical and acoustic parameters. Time was also devoted to the analysis of a technique which has been developed for the measurement of amplifier noise figure. Emphasis was placed on the requirements for designing an acoustic amplifier with the lowest possible noise figure and thus oscillation free. A technique has also been investigated wherein oscillation may be eliminated by inserting an attenuation section much as is used in an electron beam TWT amplifier. This work is coupled to the advanced development of thin-film transducers which are so vital to amplifier development.

The development of thin-film transducers has progressed to a very satisfactory point in that longitudinal-wave piezoelectric transducers are well understood and quite reproducible and shear-wave transducers appear to be very practical. The experimental work thus far completed shows that shear-wave transducers should be practical for advanced testing within the next quarterly period. Satisfactory results have also been obtained using ferromagnetic thin-film transducers. Also in order to couple rf energy into these transducers over a broad frequency band, considerations have been made to employ an rf impedance matching network.

The only thing presently blocking the testing of presently designed amplifier models is the bond making difficulties described herein. A heavy concentration will be put on this fabrication immediately and the problem should be overcome so that testing can be resumed early in the next quarter.

The results achieved thus far in the development of transducers, investigations of amplifier processes, materials, and noise measurement considerations, as well as the various fabrication and processing techniques thus far developed form a firm base for the accomplishment of this program as per the original schedule.

B. Amplifier Processes and Materials

Acoustic waves can be amplified in piezoelectric semiconductor crystals in much the same way as an electromagnetic wave is amplified in a traveling-wave tube[1,2,3,4*]. The anology being that the drift electrons

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*See Section IV for all references.

caused by a bias field across the semiconducting crystal are much like the electron beam in a TWT and the electric field caused by the acoustic wave in the piezoelectric crystal takes the place of the circuit wave in a TWT. The amplifying process can be described as follows.

When an ultrasonic wave travels through a piezoelectric crystal an alternating electric field is created. Since the crystal is also a semiconductor, this electric field causes currents to flow which in turn accumulate space charge in the crystal lattice and causes the electric field to lag the strain. The portion of this periodic space charge which is present as mobile carriers causes a modulation in the conductivity such that, when a bias field is placed across the crystal, an ac field is produced which is proportional to the modulated conductivity. Now, under the condition that the drift velocity of carriers in the medium exceeds the sonic velocity a condition is produced such that the total electric field in the medium, the sum of the field created by the acoustic wave and the field caused by the bias field across the medium with a modulated conductivity, causes the stress to lead the strain and thus deliver power to the traveling acoustic wave. Under any condition where the drift velocity does not exceed the sonic velocity the stress lags behind the strain in a piezoelectric crystal and consequently the acoustic wave is attenuated.

The equations of state for propagation of an ultrasonic wave in a piezoelectric medium, where plane wave propagation is assumed, can be written as

$$T = cS - eE \tag{1}$$

$$D = eS + \varepsilon E \tag{2}$$

where

- T = stress,
- S = strain,
- E = electric field,
- D = electric displacement,
- C = elastic constant,
- e = piezoelectric constant, and
- ε = dielectric permittivity.

These equations have been analyzed for a piezoelectric semiconductor and to follow the notation of White[2] the acoustic gain per radian, $\alpha(v/\omega)$ is represented as

$$\alpha\left(\frac{v}{\omega}\right) = \frac{K^2}{2} \frac{\dfrac{\omega_c}{\gamma\omega}}{1 + \dfrac{\omega_c^2}{\gamma^2\omega^2}\left(1 + \dfrac{\omega^2}{\omega_c\omega_D}\right)^2} \tag{3}$$

where

α = attenuation in Np/cm,

v = sonic velocity,

ω = radian frequency,

K^2 = (electromechanical coupling)$^2 \cong \dfrac{e^2}{c\varepsilon}$.

Also,

$$\omega_c = \frac{\sigma}{\varepsilon} = \text{dielectric relaxation frequency,} \tag{4}$$

$$\omega_D = \frac{v^2 q}{kT\mu f} = \text{Diffusion frequency} \tag{5}$$

where

σ = conductivity,

q = electronic charge,

k = Boltzmann constant,

T = absolute temperature,

μ = mobility, and

f = fraction of space charge present,

and

$$\gamma = 1 - \left(\frac{f\mu E_o}{v}\right) = 1 - \frac{fu_o}{v} \tag{6}$$

where

E_o = bias field, and

u_o = electron drift velocity.

It is well to point out at this time that trapping is very small and $f \cong 1$ as long as $1/\omega \ll \tau$, where τ is the relaxation time for electron trapping. From the experimental work of Uchida, et al.[5], this condition is satisfied for all frequencies of interest to this project so that f will henceforth be considered to be unity and thus will be neglected in future considerations.

Applying Eq. (3) to a specific crystal and writing the gain in units of db, one arrives at

$$G = 4.34\, K^2 \frac{\frac{L\,\omega_c}{v}\left(\frac{u_o}{v} - 1\right)}{\left(\frac{u_o}{v} - 1\right)^2 + \left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)^2} \tag{7}$$

where

L = the length of the crystal.

Since one wishes to use this crystal as an amplifier, parameters must be selected such that the device is unconditionally stable. Thus, the device must not oscillate even for complete reflection of the signal at both ends of the crystal. This means that the forward gain must not exceed the reverse attenuation which can be derived from Eq. (7) by letting v take on a negative sign. This condition can easily be shown to exist for

$$\left(\frac{u_o}{v}\right)^2 < 1 + \left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)^2 \tag{8}$$

Since Eq. (8) must hold for all frequencies the right hand side must be minimized with respect to ω, the operating frequency. Otherwise the device will be stable at the operating frequency but will break into oscillation at some other frequency. The RHS of Eq. (8) is minimized at

$$\omega^2 = \omega_c \omega_D \tag{9}$$

which is also the frequency of maximum gain, as one would expect and as can be seen by maximizing Eq. (7). The result is that Eq. (9) must hold and the bias field must be adjusted such that

$$\left(\frac{u_o}{v}\right) < \left(1 + 4\,\frac{\omega_c}{\omega_D}\right)^{\frac{1}{2}} \tag{10}$$

Using this in Eq. (7), the maximum stable gain is given by

$$G_{st}\,\frac{4.34\,K^2 L\,\frac{\omega_c}{v}\left(\sqrt{1 + 4\,\frac{\omega_c}{\omega_D}} - 1\right)}{\left(\sqrt{1 + 4\,\frac{\omega_c}{\omega_D}} - 1\right)^2 + 4\,\frac{\omega_c}{\omega_D}} \tag{11}$$

In selecting amplifier crystals it is of interest to investigate how various ratios of ω_c/ω_D effect the system. To do this, one can plot gain as a function of u_o/v for various values of ω_c/ω_D as shown in Fig. 1. A study of this figure indicates that for the sake of stability one should operate with ω_c/ω_D as large as possible. In fact, for $\omega_c/\omega_D = 0.1$ one notes that a change of only 18 percent in the bias voltage (u_o/v being a direct measure of bias) changes the gain from zero to the instability point. For higher values of ω_c/ω_D this condition is relaxed considerably. From Eqs. (4) and (5) one has

$$\frac{\omega_c}{\omega_D} = \frac{\sigma k T \mu}{\varepsilon v^2 q}\ . \tag{12}$$

Thus, one should pick a material with the highest possible mobility. Large values of conductivity also appear favorable here, but the selection of conductivity is also determined by dc power requirements and the frequency requirement of Eq. (9). Actually it is desirable to operate at high frequencies so conductivity is generally made as large as reasonably possible anyway, so for stability reasons one is still led to pick a material with as high a mobility as possible as long as the resulting gain is still high enough for the design requirements. Typical parameters of amplifier

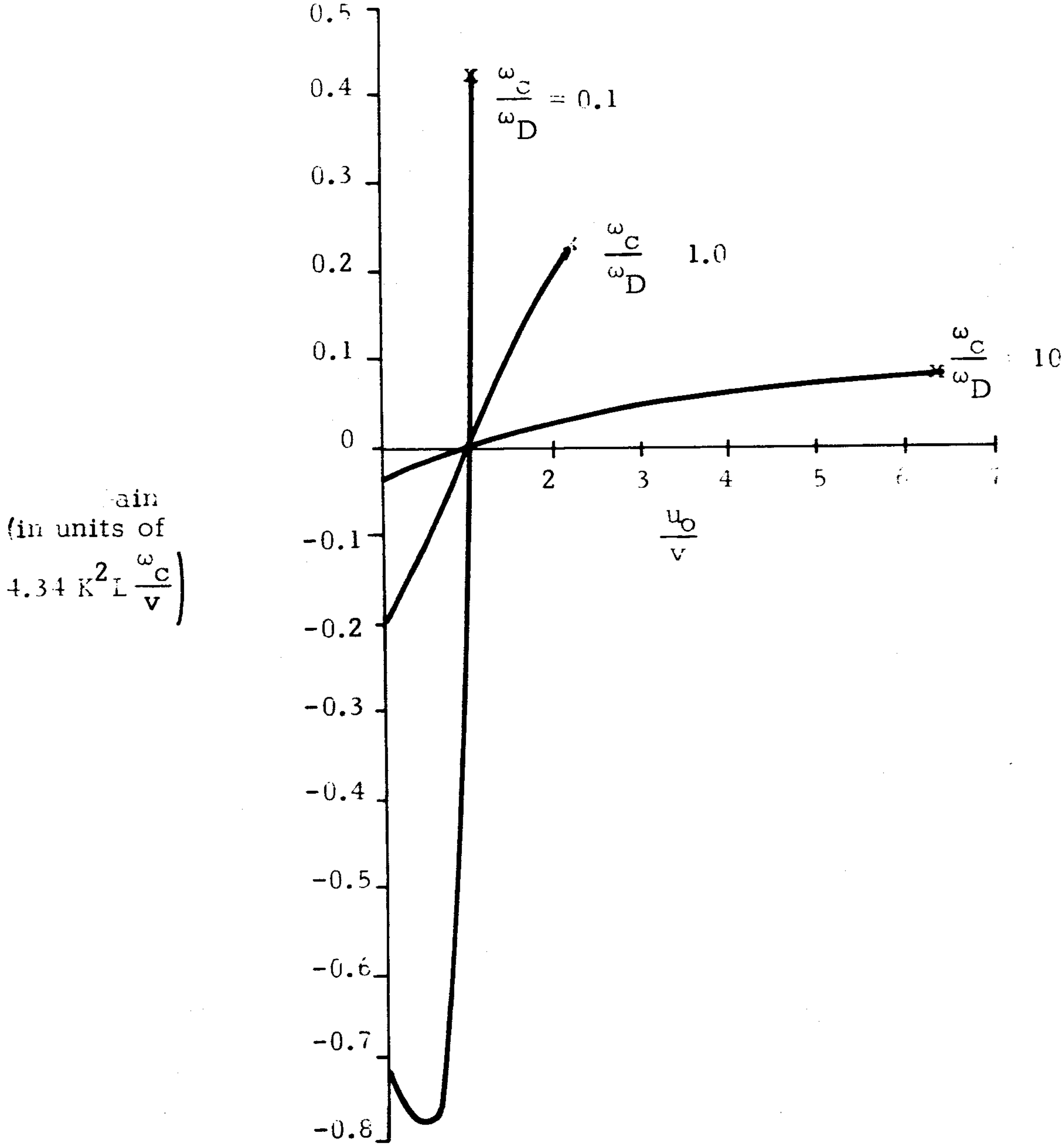


Fig. 1. Plot of gain as a function of u_o/v for various values of ω_c/ω_D.

Note: The x signifies the point where the system becomes unstable.

materials which are available are given in Table I. A quick study of this table reveals that for maximum stability one should choose GaAs or even CdSe but for high gain one is led to pick ZnO or CdS. Thus an experimental study will be necessary in order to pick out the most practical material.

As mentioned earlier, another consideration that must be made concerns the dc bias power consumed and thus heating of the system. The power consumed can be written as

$$P_o = \frac{V^2}{R} = \sigma LAE_o^2 \tag{13}$$

where

V = bias voltage,
R = resistance of amplifier as seen by the bias supply, and
A = cross section of amplifier.

If one now considers the case of maximum stable gain, the corresponding power consumed is

$$P_{st} = \frac{\sigma LA\, v^2}{\mu^2} \left(1 + 4\,\frac{\omega_c}{\omega_D}\right) \tag{14}$$

From this and Eq. (11) one can get the ratio of power consumed per db of electronic gain

$$\frac{P_{st}}{G_{st}} = \frac{2\sigma A\, v^3}{4.34\,\mu^2 K^2 \omega_c} \left(1 + 4\,\frac{\omega_c}{\omega_D}\right)^{3/2} \frac{\text{watts}}{\text{db}} \tag{15}$$

Equation (15), thus, gives a good means of comparing the parameters of various crystals as far as efficiency is concerned. A better way is to calculate the power consumed per db of actual gain; however, sufficient data is not presently available concerning the acoustic attenuation in the materials of interest. To give the reader another comparison of the materials listed in Table I, Eq. (15) is plotted as a function of frequency in Fig. 2.

TABLE I

Typical Parameters for Amplifier Materials

Material	Mode	ω_C (σ in $\Omega^{-1}cm^{-1}$)	ω_D (at 300°K)	K^2	$v\left(\frac{cm}{sec}\right)$	$\mu\left(\frac{cm^2}{V sec}\right.$ at 300°K)	References
CdS	Long.	$1.2 \times 10^{12}\sigma$	2.9×10^{10}	0.04	4.3×10^5	250	(1)
CdS	Shear	$1.25 \times 10^{12}\sigma$	4.8×10^9	0.036	1.75×10^5	250	(1)
GaAs	Shear	$10^{12}\sigma$	7×10^8	0.0024	3.35×10^5	5800	(1)
ZnO	Long.	$1.37 \times 10^{12}\sigma$	7.2×10^{10}	0.115	6.1×10^5	200	(6) (7)
ZnO	Shear	$1.37 \times 10^{12}\sigma$	1.4×10^{10}	0.053	2.73×10^5	200	(6) (7)
CdSe	Long.	$1.11 \times 10^{12}\sigma$	9.3×10^9	0.017	3.8×10^5	600	(7)
CdSe	Shear	$1.2 \times 10^{12}\sigma$	1.45×10^9	0.017	1.5×10^5	600	(7)

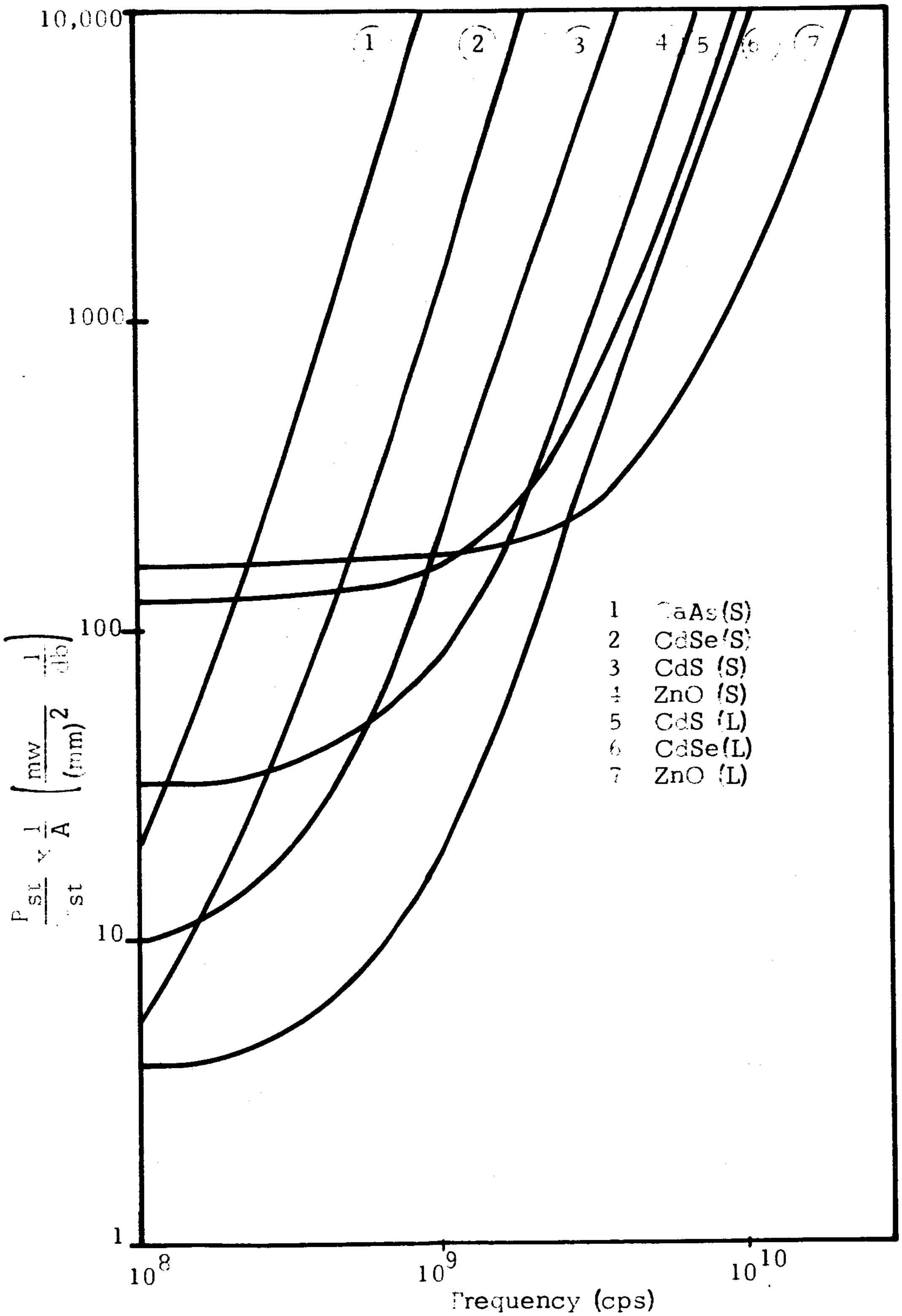
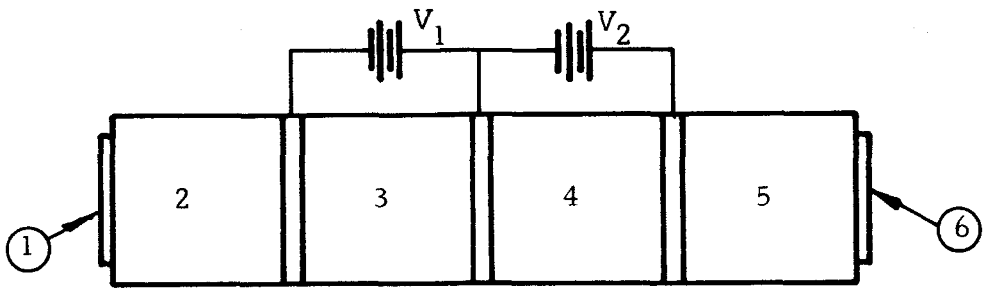


Fig. 2. Bias power consumed as a function of frequency under condition of maximum stable gain.

The reader should keep in mind that Fig. 2 is plotted under the restriction of maximum stable gain and not maximum gain or maximum efficiency. Because of previous problems with amplifier oscillations, as experienced by other researchers, the initial amplifier designs will follow the criterion of stability as suggested above.

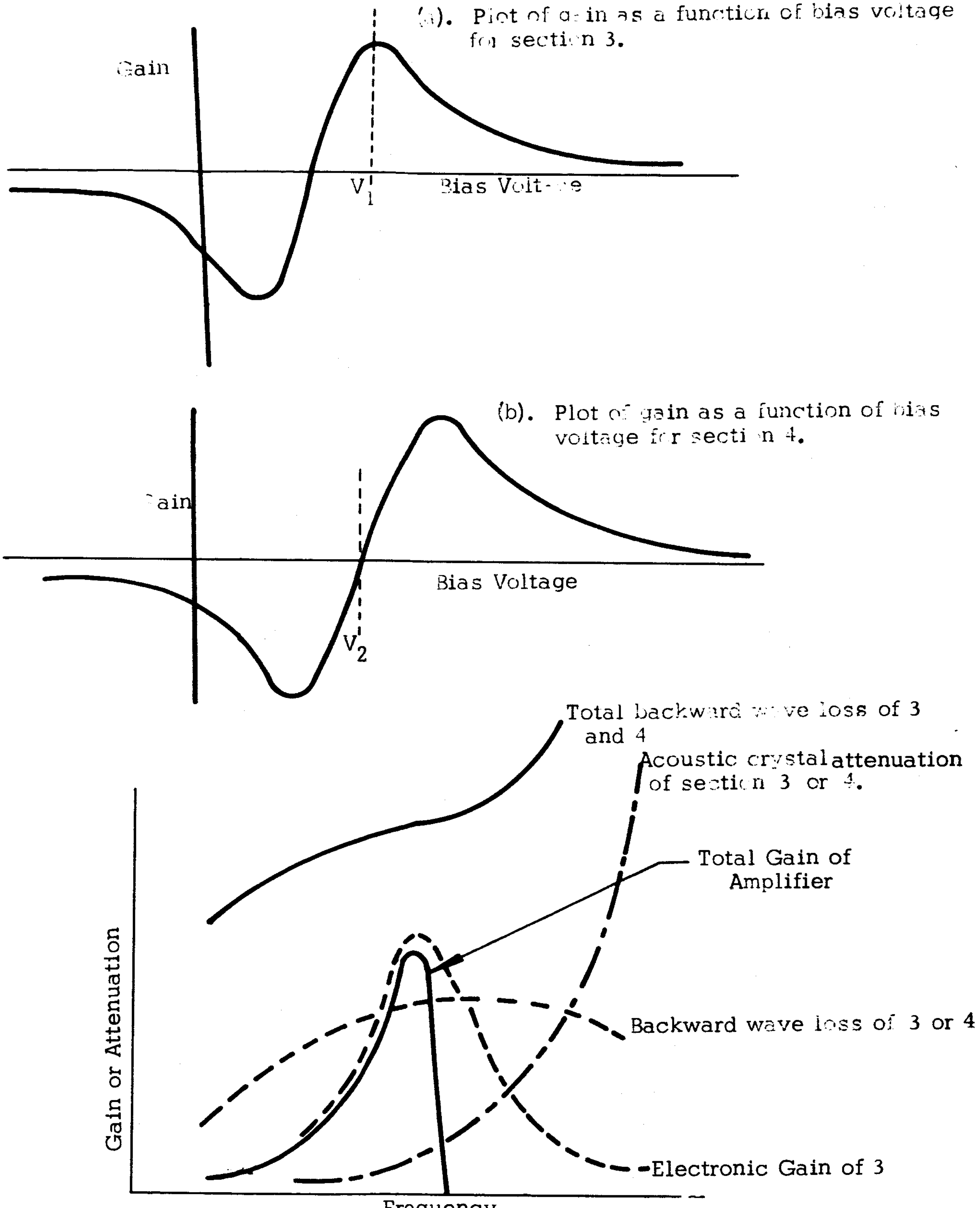
Analysis has, however, been conducted concerning ways of increasing the maximum gain and/or efficiency, and as time and importance specify, they will be incorporated into the amplifier.

It was concern for oscillations in the amplifier which resulted in the restrictions of Eqs. (9) and (10). It has been suggested by May[8] that these criterion can be relaxed by using an attenuator section which is very much like the amplifying section except that the bias voltage is adjusted so as to operate with no gain or attenuation in the forward direction but with attenuation in the backward direction. This is suggested by Fig. 3, and the crude curves drawn in Fig. 4. (These are not calculated curves and they are only meant to be suggestive of the data reported by May.)



1. Input Transducer
2, 5, Buffer Crystals
3. Amplifier Section
4. Attenuator Section as Suggested by May
6. Output Transducer

Fig. 3. Acoustic amplifier with attenuator section incorporated.



(a). Plot of gain as a function of bias voltage for section 3.

(b). Plot of gain as a function of bias voltage for section 4.

(c) Plots of gain and loss for the device with and without attenuator being used.

Fig. 4. Typical characteristic curves for the amplifier and attenuator sections of the device suggested in Fig. 3.

As can be seen from Fig. 4, without the attenuator section there is a frequency where the forward gain is larger than the backward attenuation and thus an unstable condition depending on end reflections. This is then overcome by the attenuator section which essentially doubles the backward wave attenuation but does not appreciably affect the forward wave gain. This scheme appears very attractive and in fact, is very similar to the way oscillations are kept from building up in electron-beam TWTs. The scheme does, however, make the device slightly more complicated and one must remember that reflections off the boundaries of section (3) of Fig. 3 will still allow oscillations to build up in that section. This demands low reflectivity bonds around section (3) which may or may not be presently available.

Figures 3 and 4 have demonstrated how maximum gain can be obtained from the amplifier crystal. It is also of interest to investigate the conditions for minimum bias-power consumption for a given gain and frequency requirement. To do this it is still desirable to maintain the stability criterion of Eq. (3) so that one need not be overly concerned with reflections. It is very difficult to determine minimum dc power consumption for a completely general case so this will not be treated here except to make several comments about this condition. Let it be sufficient to note that the necessary calculations have been made for several special cases with given requirements of bandwidth, gain and frequency, and the conditions of minimum bias power have been determined.

In the above work two requirements have been met, both of which, when relaxed, will yield higher efficiency. These requirements are

$$\omega^2 = \omega_c \omega_D \tag{16}$$

and

$$\frac{u_o}{v} = \left(1 + 4 \frac{\omega_c}{\omega_D} \right)^{\frac{1}{2}} \tag{17}$$

One can verify, by taking a specific example, that efficiency is increased if one lets

$$\omega^2 = a\,\omega_c \omega_D \qquad (18)$$

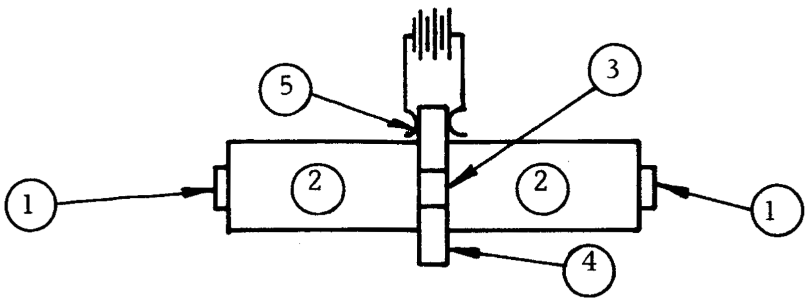
and

$$\frac{u_o}{v} = b \;\; 1 + 4\,\frac{\omega_c}{\omega_D} \;\; ^{\frac{1}{2}} \qquad (19)$$

where $a > 1$ and/or $b < 1$. Equation (18) amounts to operating at a frequency which is higher than the frequency at which maximum gain occurs. Thus, using this criterion, one must make special arrangements so that noise of a lower frequency than that of the signal does not build up. Equation (19) amounts to operating at a bias voltage which is somewhat less than that at which instability occurs. For a given value of gain this may amount to making the amplifier section longer than its minimum length so that better efficiency can be appreciated. Also, one should keep in mind that, depending on the final application of the amplifier, noise considerations should be made. These considerations are also dependent on the crystal length.

Since the bias power varies directly as the cross-sectional area of the amplifier, and gain is not affected by this dimension, it is of prime advantage to make the area as small as possible. This will have some limitation on the maximum acoustic beam size, but from past experience at MEC small beam diameters of the order of 0.025 inch are quite easy to generate efficiently. To keep the device quite rigid and of enough mass so that heat dissipation will be no problem, it has been decided to pot the amplifier in epoxy and put the compound amplifier section in place of the previously used amplifier wafer as shown in Fig. 5.

The amplifier crystal must be potted in a clear, nonconducting, rigid potting compound whose lapping and polishing characteristics are similar



1. Transducers   2. Buffer Crystals   3. Amplifier Crystal
4. Epoxy   5. Ohmic Bias Contacts

Fig. 5. Cross sectional view of acoustic amplifier.

to those of the amplifying crystal and whose curing and temperature properties are appropriate. The hardest combination of requirements to satisfy simultaneously are that the potting compound be clear (so that the amplifier crystal's conductivity can be adjusted with light as it can in CdS), be able to withstand the temperatures used in bonding, and at the same time have lapping and polishing characteristics similar to the amplifying crystal. Since it has been decided to use CdS as a basic experimental material, because of its good characteristics and availability in good single crystals, the research thus far has been centered around finding an appropriate compound for potting small CdS crystals. The best material that could be found was Maraglas 665A, crystal-clear thermosetting plastic[9]. It has been demonstrated that this compound fulfills all requirements with the possible exception of the thermal requirements during bonding, which have not as yet been tested. All indications are, however, that this requirement will also be satisfied.

It is well to mention that the lapping and polishing techniques are quite specialized in that some abrasives wear away the two materials at different rates. It was found that if 30 micron diamond paste was used for the rough lapping abrasive (this wears the materials at different rates) and then the final lapping and polishing were carried out using first 1-micron alumina powder in a water solution and then 0.3 micron alumina in a water solution on silk, then the final crystal can be made to have surfaces which are both plane and parallel, as they must be. The photograph of Fig. 6 shows an example of a potted amplifier section which was constructed as suggested above.

C. Noise Figure

Oscillations and noise sources are of prime interest to this project so a method has been devised that will measure the noise figure of the amplifier. This method incorporates the design of optimum length buffer crystals used in conjunction with an amplifier section whose gain is set equal to the loss in the total structure. This allows one to admit a signal at the input and keep the signal reflecting back and forth in the device, being amplified each time it passes through the amplifier section, until it is lost in the noise which will build up in the system. A measure of the time required to saturate the signal with noise gives a direct measurement of the noise figure of the amplifier. As long as oscillations occur in the amplifier this noise figure will be quite high, say 10^4 or even 10^6, but once oscillations are omitted then the noise figure will decrease significantly. It is felt that a reasonable value of noise figure to work for is that obtained when considering shot noise. This situation has been analyzed by Quate[10] and he arrives at the value

$$F_g = 1 + \left(\frac{q}{4\ kT}\right) \frac{u_o}{\mu} \ \frac{v}{\omega} \ \frac{\omega_c}{\omega} \left(\frac{\omega_D}{\omega}\right)^2 K^2 \qquad (20)$$

To get an idea of what this value might be one can check the example of longitudinal waves in CdS at room temperature. If the device is adjusted to have maximum stable gain then the noise figure of the amplifier will be about $F_g = 1.19$. With the present state of the art this can be thought of as a very optimistic value.

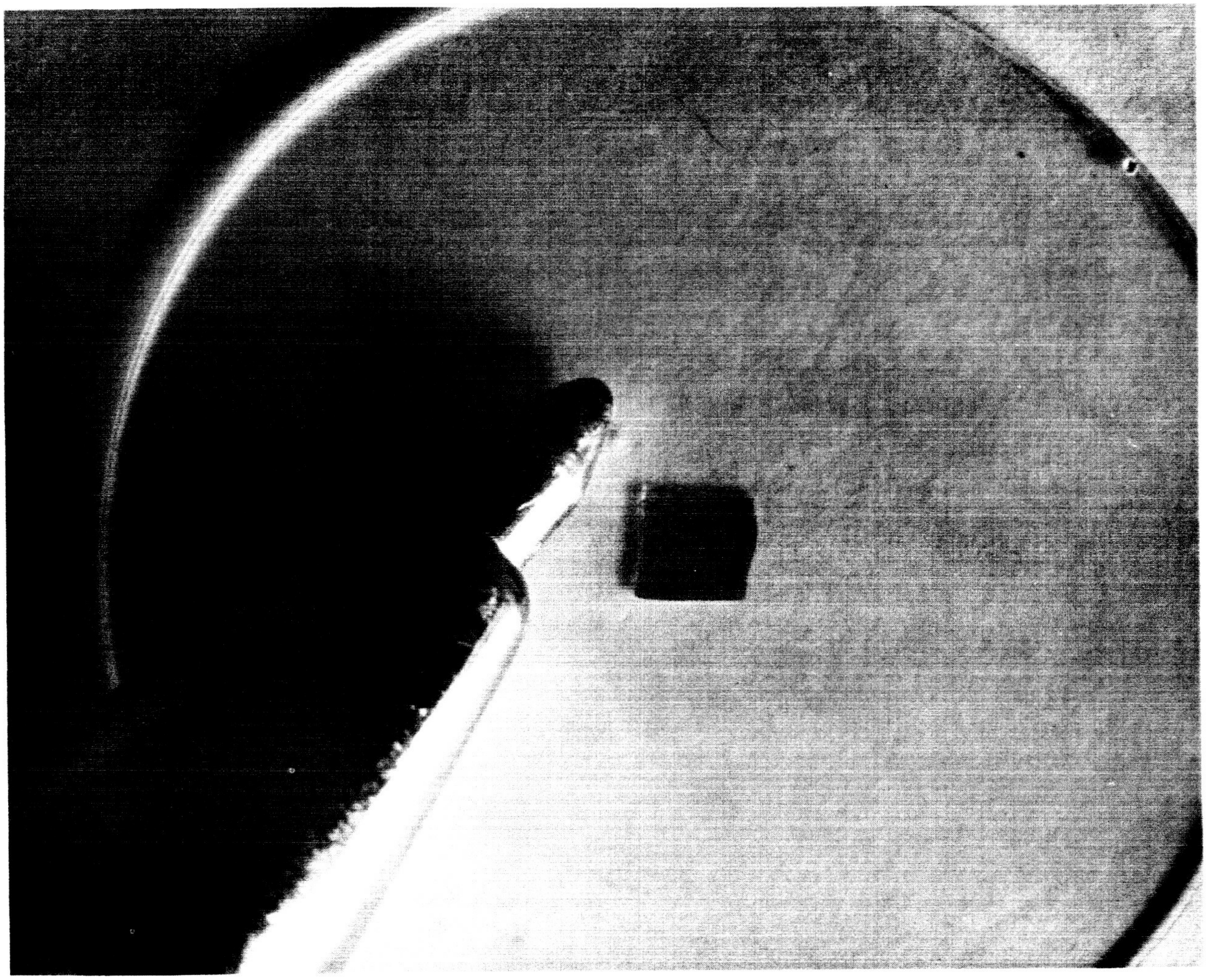


Fig. 6. Photograph of potted amplifier section.

D. Fabrication of Amplifier Model

An initial experimental amplifier model was designed and fabricated during this period as shown in Fig. 7. This model was designed to amplify acoustic signals at 1.1 Gc. The buffer rods are Z-quartz (1.3 centimeters long) with thin-film CdS longitudinal-wave transducers deposited on each end. Each transducer was measured to have a conversion efficiency of -15 db. The amplifier section is made up of a 0.020-inch thick, grade A CdS wafer, polished flat and parallel and bonded to the quartz delay rod with indium. The entire unit has been potted into its coupling circuit for rigidity. Drift field connections were made to the surfaces of the CdS waver as shown. This particular amplifier unit did not operate as well as expected due to poor acoustic bonds between the propagation crystals and the amplifier crystal. Tests of the device revealed that much of the acoustic power was being reflected from the bonds on each interface. These reflections were sufficiently strong to negate the improvement in delay performance provided by the amplifier.

The bonds used in this first-model amplifier unit were quite thick (about 500 Angstroms); however, this should not account for their nontransmission properties. The temperature was also not optimum when these bonds were fabricated. Experiments are presently being carried out to improve the reliability of the bonding technique and to simplify the rather complex assembly procedure for the multielement amplifier units. As the bonding and assembly techniques are refined another amplifier of a similar configuration will be assembled and tested. The next model will, however, be made using special optically-selected CdS crystals which were purchased from Clevite. These crystals are photoconducting with possible values of conductivity as high as about 10^3 per ohm centimeter under high filtered illumination.

In order to improve conversion efficiency over substantial bandwidths, using piezoelectric thin-film transducers, analyses have been performed on broadband rf-impedance matching networks. The first step in optimizing the

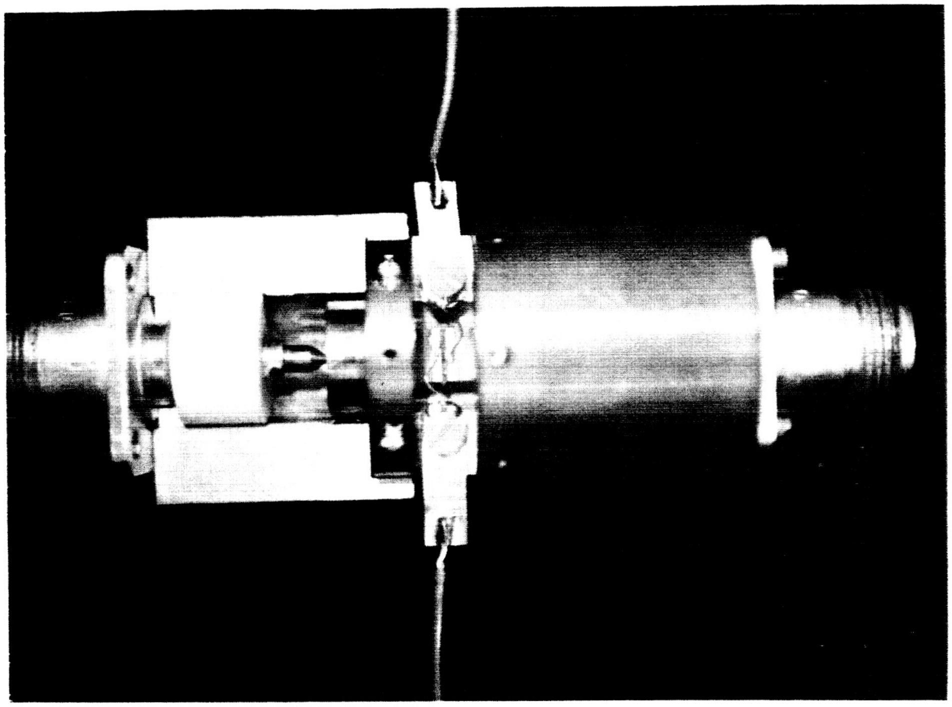
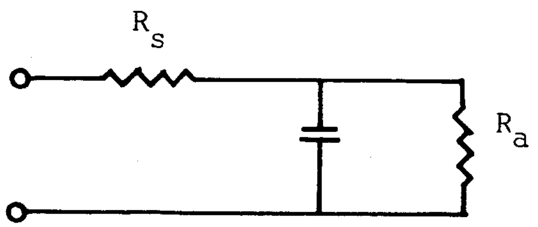


Fig. 7. Photograph of amplifier model using CdS thin-film transducers on Z-quartz and integrated CdS amplifier.

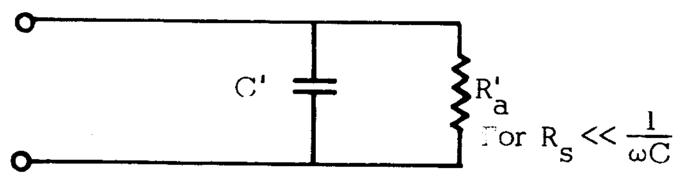
electromagnetic circuit is to characterize the transducer in an equivalent circuit. The measured equivalent circuit for a CdS thin-film transducer consists of a resistance, R_s, in series with a parallel combination of a capacitance, C, and a resistance R_a, as shown in Fig. 8. R_s is the resistance of the film contacts, C is the capacitance of the insulating film, and R_a is the effective load resistance presented by the acoustic system. Since the objective is to maximize the power transferred to R_a, it is important to minimize both C and R_s. In particular, if R_s can be made small compared to $1/\omega_c$, essentially all of the voltage will appear across the parallel equivalent components as shown in the figure.

Filter design theory has been applied to develop a matching network which will provide both high efficiency and wideband operation. The first section of such a network is shown in the figure for a CdS film transducer with a center frequency of 1.5 Gc. Means for realizing this electrical network in the microwave circuit are being investigated.

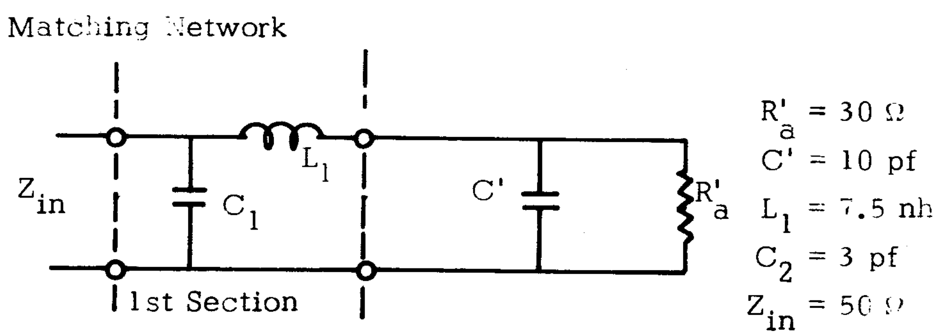
Because of the complexities experienced in producing suitable acoustic bonds between amplifier and propagation crystals, it is worthwhile to describe the bonding procedures. The first quarterly report showed a photo of the apparatus used for bonding acoustic crystals. A CdS wafer is chemically cleaned and attached to the end of an optically-flat quartz holder. This assembly is mounted on an arm attached to a rotary push-pull feedthrough in the vacuum station with the exposed side of the CdS facing downward. While the station is being evacuated, the CdS wafer is ion-bombarded to remove the surface layer of sulphur atoms and leave a thin layer of cadmium atoms. A thin film of indium is evaporated onto this surface and the wafer is then swung over the bonding apparatus. The apparatus consists of a holder for the buffer crystal and a vacuum bellows. By applying a gas pressure to the bellows (typically 20 pounds), the two crystals are compressed together and automatically align themselves by pivoting on a ball bearing on which the buffer crystal rides. The bonding interface is then heated with a coil and allowed to cool.



a. Transducer equivalent circuit.



b. Transformed equivalent circuit.



c. Electromagnetic matching network.

Fig. 8. Coupling circuits for optimum acoustic transducer efficiency and bandwidth (CdS film transducer at 1.5 Gc).

There are apparently two problems with the present method. First, a very small amount of regular vacuum grease was used to hold the CdS wafer in place during the operation. This grease apparently would flow under temperature and pressure. It has been suggested that there is a special grease available which will overcome this problem. Second, it appears as though the combination of pressure and temperature is relatively critical. The technique now being developed involves heating the interface very accurately and holding the bond under pressure for several hours. Also bond thicknesses of about one-half wavelength are to be used to minimize reflections.

E. Transducer Development

The last quarterly report contained a section describing the operation and present techniques involved in development of piezoelectric longitudinal-wave transducers. Since that time some work has been initiated in the field of shear-wave piezoelectric transducers and ferromagnetic transducers. Following is a brief discussion of the work to date.

1. Thin-film shear-wave transducers

One of the general properties of evaporated CdS films is their tendency to be deposited with the "C" axis of the crystal oriented normal to the substrate surface. This makes the generation of shear waves nearly impossible since the efficient generation of shear waves requires that the "C" axis be in the plane of the transducer. It is possible to shift the axis away from the normal by a strong annealing of the film, but this is a rather undesirable attack on the problem because it has a tendency to cause random microscopic recrystallization of the film and subsequent mechanical fractures. A new method used and reported by Foster[11] shows that films can be deposited on an inclined substrate and the axes remain oriented at this evaporation angle. These transducers were shown to be nearly as efficient in the generation of shear waves as normal-axis transducers were in the generation of longitudinal waves. In addition, the discrimination between the two types of waves was greater than 30 db in most cases. In view of these reported results, an apparatus has been designed and used to evaporate thin-film CdS shear-wave transducers. The results have been checked and appeared very favorable; however, due to the preliminary nature of the measurements the results will not be described here but will be reported as soon as verified and completed. The resulting transducers, if suitably reliable and efficient, will be used in future amplifier experiments.

2. Ferromagnetic transducers

Nickel and nickel-alloy thin films have the capability of being efficient high frequency high power acoustic transducers[12]. Calculations have now been undertaken to determine the optimum coupling structure to be used with these films.

The coupling structure desired must be capable of producing an intense rf magnetic field at the film's surfaces and also must be capable of operating over a broad frequency range. The dielectric resonator coupler[13] is an efficient means of concentrating rf magnetic field into a small volume, but imposes an important limitation in bandwidth due to large values of resonator Q.

The shorted coaxial coupling scheme[13] has the advantage of large operable bandwidth. However, no theoretical comparison has been made on relative magnetic field strengths of the dielectric resonator coupler and the shorted coaxial coupler. Calculations, assuming a given power input, have now been been completed to compare these coupling techniques.

For a given power input, the maximum magnetic field obtained in the dielectric resonator is given by

$$|H|_{max} = 26 \sqrt{\frac{1.8\, P_{in} Q}{\eta}}\, \frac{f}{c} \; . \tag{21}$$

Assuming

$$Q = 1000,$$
$$f = 3 \text{ Gc, and}$$
$$\eta = 377 \text{ ohms,}$$

then

$$\left|H\right|_{max} = 580 \sqrt{P_{in}} \ \frac{\text{amps}}{\text{meter}} . \tag{22}$$

For the shorted coaxial system the maximum field is given by

$$\left|H_{\theta}\right|_{max} = \frac{0.063 \sqrt{P_{in}}}{r} \ \frac{\text{amps}}{\text{meter}} , \tag{23}$$

where r is the distance from the center conductor. For r = 0.010 inch

$$\left|H_{\theta}\right|_{max} = 248 \sqrt{P_{in}} \ \frac{\text{amps}}{\text{meter}} . \tag{24}$$

From the above calculations one would expect only a slight degradation in conversion efficiency using the shorted coaxial system. Preliminary experimental results at 1800 Mc show a conversion efficiency of -33 db with the dielectric resonator and -40 db with the coaxial system. Since the inherent efficiency of the magnetic transducers improves by as much as 20 db as one goes up in frequency, it is expected that nickel film transducers in the coaxial coupler structure will be extremely useful in the development of higher frequency microwave devices.

Using the coaxial structure, the bandwidth of the ferromagnetic film transducer should be limited only by the linewidth of the film. The linewidth of the magnetic film is far more important in limiting the bandwidth of the transducer than the change in effective thickness of the film with frequency. From linewidth measurements of nickel, it is calculated that bandwidths on the order of 8 percent to 16 percent should be obtained, and first measurements with the coaxial structure produced transducer bandwidths of greater than 10 percent. This can be compared to bandwidths of a fraction of 1 percent using the dielectric resonator coupler.

A point of previous concern was the fact that the coaxial coupler produced rf magnetic fields that were less uniform than those produced by the dielectric resonator. However experiments show no apparent difference in the waves generated by the two methods.

II. PROGRAM FOR NEXT REPORTING INTERVAL

The theoretical analysis of transducer techniques, impedance matching techniques, oscillation suppression mechanisms, reduction of noise, and materials investigation will continue. The experimental portion of the program will emphasize further improvement of microwave acoustic amplifier models with special considerations given to oscillation free amplification. Specific tasks will include:

- development of a reliable bond making procedure,
- design, fabrication, and testing of advanced experimental amplifier models,
- initial measurements of amplifier properties,
- development of reliable techniques of making shear wave piezoelectric thin-film transducers, and
- advanced development of longitudinal-wave piezoelectric thin-film transducers.

Efforts will also be devoted to fabrication techniques necessary for the rather complex amplifier assemblies necessary for this program.

III. CONCLUSIONS AND RECOMMENDATIONS

From the analysis presented in this report it can be concluded that there are at least three materials, CdS, CdSe, and ZnO, which have relatively good characteristics when the discussed stability criteria are invoked. These materials, when operated as longitudinal-wave amplifiers, show the lowest power consumed per db of gain when operating in the 1- to 10-Gc region of the spectrum. It is well to keep in mind that shear-wave amplifiers are still to great advantage if future experimental work allows the relaxation of the stability requirements or if it is found that amplifier efficiency is not as important as presently considered.

The development of thin-film transducers has progressed to a very satisfactory point in that longitudinal-wave piezoelectric transducers are well understood and quite reproducible and shear-wave transducers appear to be very practical. The experimental work thus far completed shows that shear-wave transducers should be practical for advanced testing within the next quarterly period. Satisfactory results have also been obtained using ferromagnetic thin-film transducers.

The only thing presently blocking the testing of presently designed amplifier models is the bond-making difficulties discussed herein. A heavy concentration will be put on this fabrication immediately and the problem should be overcome so that testing can continue early in the next quarter.

The results achieved thus far in the development of transducers, investigations of amplifier processes, noise measurement techniques, and material considerations, as well as the various fabrication and processing techniques thus far developed form a firm base for the accomplishment of this program as per the original schedule.

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